High Performance Solutions for the Thermal Management of Electronics in Harsh Environments

Mark Montesano, Vice President of engineering, k Technology, a Division of Thermacore

The range of applications and functions of military electronics is rapidly expanding. From smart weapons to unmanned vehicles, the challenge of packaging significant processing power in very limited volumes that need to survive extremely harsh environments is rising. Combined with the quest for miniaturization, the power densities of these systems are rapidly accelerating. These high packaging densities are causing high thermal dissipation fluxes and if not efficiently managed, device temperatures will increase above tolerable levels.

The recent trend toward higher performance payloads for near-term military defense and space communication missions has led to more demanding thermal requirements (e.g., higher power density of the microelectronics package, closely matched thermal expansion of materials, unit reliability) and structural (e.g., reduced weight) requirements. New applications such as phased array radars, satellite communication links, aircraft avionics and solid-state power converter units, among others, as well as new packaging technologies like multi-chip modules have increased the technical challenges in packaging these systems. Managing these high packaging densities and their corresponding high power dissipations requires the use of thermal systems capable of maintaining device temperatures below critical levels for all environments.

Encapsulated annealed pyrolytic graphite, named k-Core, is a material system that can satisfy many of the packaging requirements of such systems. Encapsulated annealed pyrolytic graphite (APG) materials enable the increase of power densities by four to five times relative to baseline solutions due to the materials' high conductance. This can be accomplished without adding mass or reducing system reliability.

APG is highly aligned crystalline graphite with an in-plane thermal conductivity of four times that of copper. It is a manufactured material produced by thermal cracking of a hydrocarbon gas and deposition under low pressure and afterward annealing the deposit to form a highly crystalline hexagonal graphite structure. The APG is used as an insert in k-Core components encapsulated by a structural shell.

The shell material can be any metal (e.g., aluminum, copper, nickel, invar, magnesium), any composite (e.g. carbon fiber composite, carbon-carbon composite, metal matrix composite), plastic or ceramic. Because the encapsulating shell completely surrounds and seals the APG insert, traditional finishing processes such as machining, plating, painting and assembly can be used without modification. This feature allows the seamless use of this materials technology in these demanding applications.

Encapsulated APG materials are qualified and have a significant heritage in space, air and sea. They are critical components on many DoD systems including radars, power supplies, converters and processors. This ideal thermal management material has high thermal conductivity (up to1,400 W/mK), low mass density (as low as 1.9 g/cm3), high stiffness (up to 50 Msi) and the ability to have an engineered coefficient of thermal expansion (CTE).

High Performance Material Solution -- Encapsulated APG
The k Technology Division of Thermacore has developed and patented a technique of encapsulating APG within a structural shell. This macro-composite is an ideal thermal management material because of its high thermal conductivity, low density, and engineered structural properties, including CTE. The patented encapsulation technique permits intimate contact between the encapsulation material and the APG insert or inserts while concurrently allowing the structural decoupling of the two. There is no shear force transfer across the encapsulant/APG interface, (see Figure 1). This permits each component to be optimized independently.

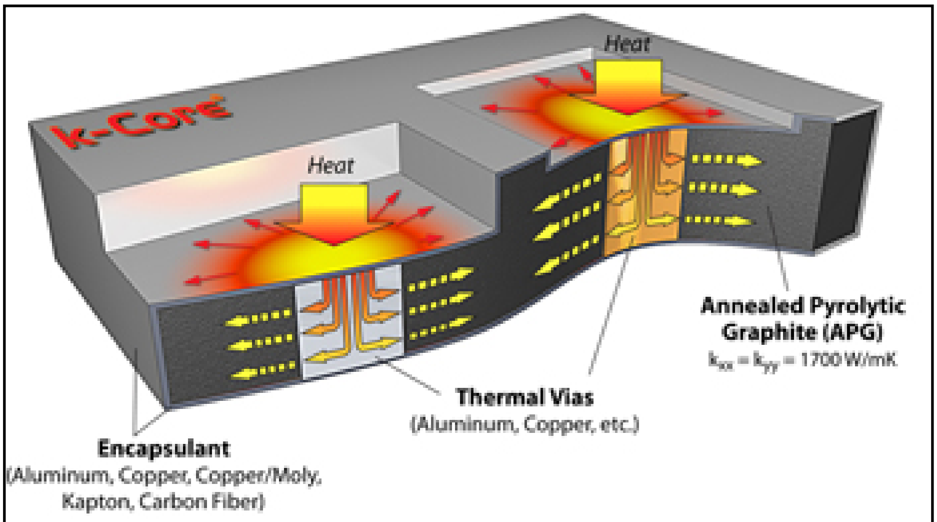


Figure 1 The encapsulated APG material has three times the conductivity of copper with a mass density less than that of aluminum. The APG insert provides a high k path while the encapsulating shell sets the CTE and structural properties. Thermal vias may be used to increase the conductance into the APG.

APG's highly aligned crystalline structure has an in-plane thermal conductivity of 1,700 W/mK, which is four times that of copper, and has a mass density of 2.2 g/cm3, which is 30 percent below that of aluminum. The high thermal conductivity, as well as high strength properties of APG, run parallel to the hexagonal layer lattice (ab or basal plane). However, APG graphite overall has poor mechanical properties because of the weak van der Waals' forces that bond the lattice in the c axis. Encapsulating APG within a structural shell addresses this structural limitation. The resulting composite derives its high conductance from the APG insert and its structural integrate that form the encapsulating shell. The APG encapsulation scheme combines the desired properties of two materials in a configuration that allows the cost-effective optimization of the assembly.

Material	Thermal Conductivity (W/mK)	Density (g/cm^3)	Coef. of Thermal Expansion (ppm/K)	Specific Conductivity (conductivity/density.W/mK/g/cm^3)
Copper (OFHC)	390.0	8.90	16.9	43.8
Beryllium	220.0	1.80	13.5	122.2
Aluminum Beryllium (62% Be)	210.0	2.10	13.9	100.0
Aluminum (6061)	180.0	2.80	23.6	64.3
AlSi (40% Si)	126.0	2.53	15.0	49.8
Magnisium (AZM)	79.0	1.80	27.3	43.9
Kovar	14.0	8.40	5.9	1.7

Table 1. Common electronic packaging materials. The relatively high specific conductivity of aluminum combined with its affordability explains its wide use as a heat sink material for space and airborne applications.

Specific thermal conductivity can be defined as the thermal conductivity per unit mass. Specific thermal conductivity is a useful unit of measure in the evaluation of heat sinks for mobile systems where both high conductivity and low mass are desired properties. Table 1 lists the properties of several common packaging materials. Note the outstanding specific conductivity of the beryllium and beryllium composite materials. Aluminum is another material with high specific conductance and because it is an affordable material, it is a widely used packaging material in mobile applications.

These listed materials, when used as the shell in an encapsulated APG heat sink, can have extremely high specific thermal conductivity values (Table 2). Magnesium is a poor thermal conductor (compared with aluminum) but its low density makes it ideal for weight-sensitive applications. Combining this low-density material with APG addresses magnesium's low conductivity, resulting in a composite with a specific conductivity greater than four times that of beryllium.

Material	Thermal Conductivity (W/mK)	Density (g/cm^3)	Coef. of Thermal Expansion (ppm/K)	Specific Conductivity (conductivity/density. W/mK/g/cm^3)
Copper (OFHC) w APG insert	1176.0	4.92	16.9	239.2
Berylliumw APG insert	1108.0	2.08	13.5	533.7
Aluminum Beryllium (62% Be) w APG insert	1104.0	2.20	13.9	502.7
Aluminum (6061) w APG insert	1092.0	2.48	23.6	441.0
AlSi (40% Si) w APG insert	1070.4	2.37	15.0	452.0
Magnisium (AZM) w APG insert	1051.6	2.08	27.3	506.6
Kovar w APG insert	1025.6	4.72	5.9	217.5

Table 2. Encapsulated APG components with common electronic packaging materials as the encapsulating shell. The calculated values are for in-plane heat flow with a 60 percent volume fraction of the APG insert.

In addition to the outstanding thermal performance and low density, these parts can have favorable CTE properties. For example, an encapsulated APG part using the encapsulation material Kovar has both high specific thermal conductivity (218 W/mK/g/cm3) and low CTE (5.9 ppm/K). In electronic packaging designs, the CTE of the heat sink typically must match that of a ceramic packaged device, which is typically between 5 and 8 ppm/K. The packaging material Kovar is primarily used because its CTE is a close match to silicon and gallium arsenide devices. Unfortunately, the low thermal conductivity of Kovar limits its use in high power devices. By selecting Kovar as the encapsulation material, all the benefits of Kovar can be realized with the addition of high thermal conductivity.

APG is orthotropic and as such the direction of the thermal loading may also determine the thermal performance of the heat sink. The low through-the-thickness (TTT) thermal conductivity of the APG can lower the effective thermal conductivity of the part when there is a thermal path normal to the plane of the APG. For most applications, this characteristic is small because the high in-plane conductivity of the APG quickly spreads the heat, thus lowering the thermal density (Q/A). At the reduced thermal density, the temperature rise TTT is significantly reduced. However, designs that require a high-flux density energy (>10w/cm2) heat path normal to the plane of the APG, the temperature rise can be significant.

In such applications, where the spreading within the APG is insufficient, thermal vias may be used. Thermal vias effectively provide a through-plane conductivity equal to that of the encapsulation material. For example, for an application using a copper/tungsten encapsulant, the thermal vias would improve the TTT conductivity from 10 W/mK to 230 W/mK. These inserts are effective because the conduction length TTT is typically small (Figure 3).

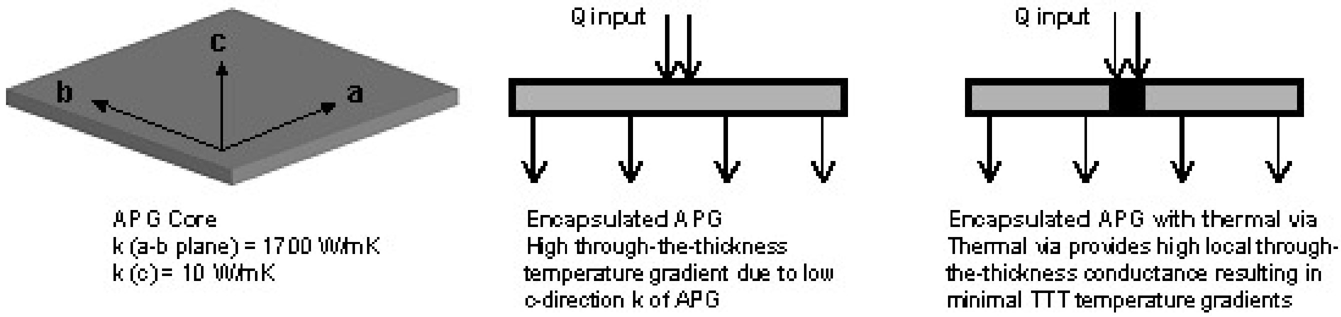


Figure 3. The placement of a thermal via will improve the through-the-thickness conductivity to that of the encapsulation material.

Power Supply Chassis Example: Encapsulated APG Boosts Thermal Performance in a Power Supply Chassis

A common use of the encapsulate APG material system is for conduction-cooled airborne power supply chassis. These power converters typically dissipate high power at high power flux densities and as such, solid aluminum designs results in unacceptably high device temperatures. Changing to solid copper is typically not an option due to weight constraints.

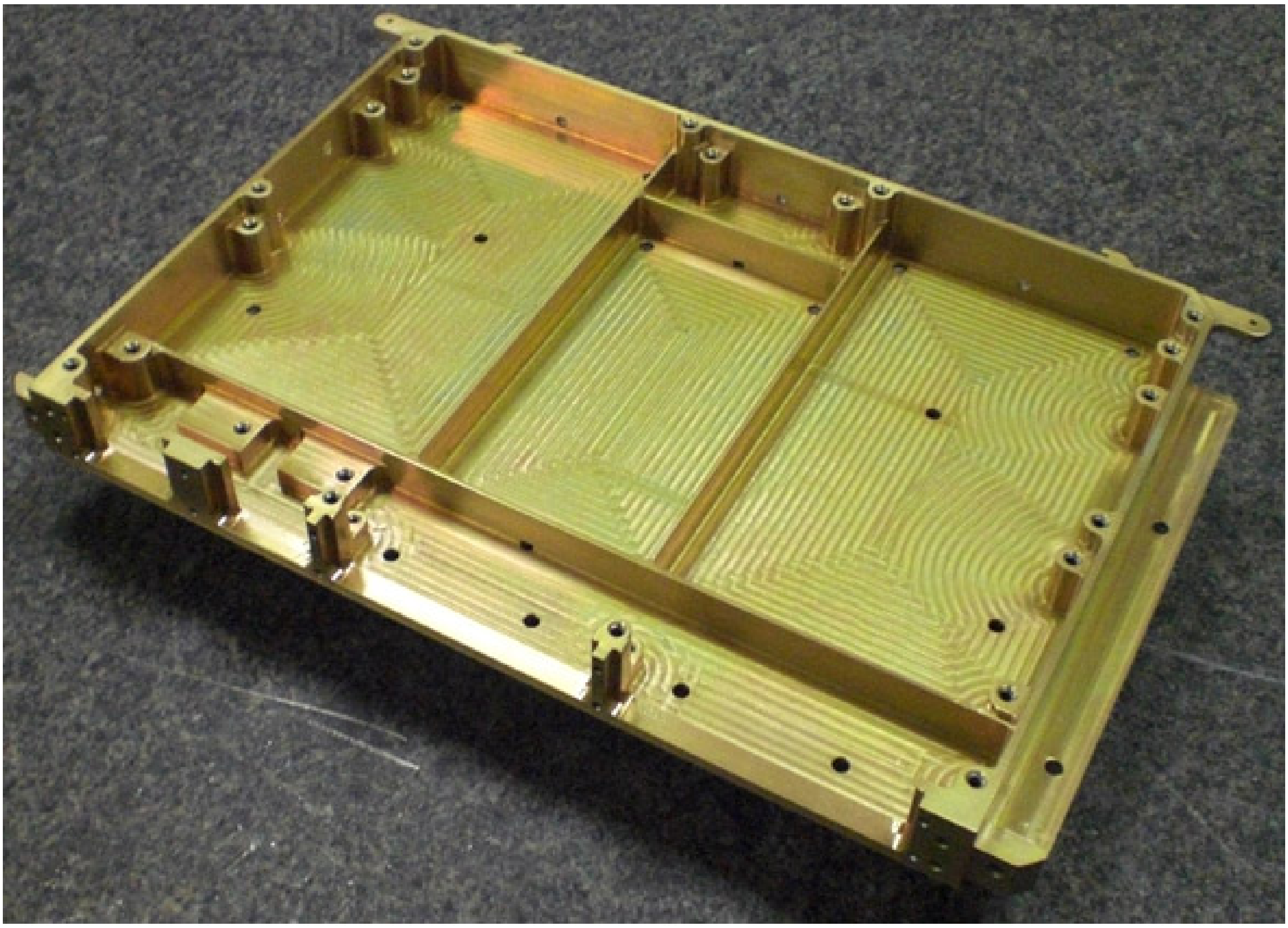
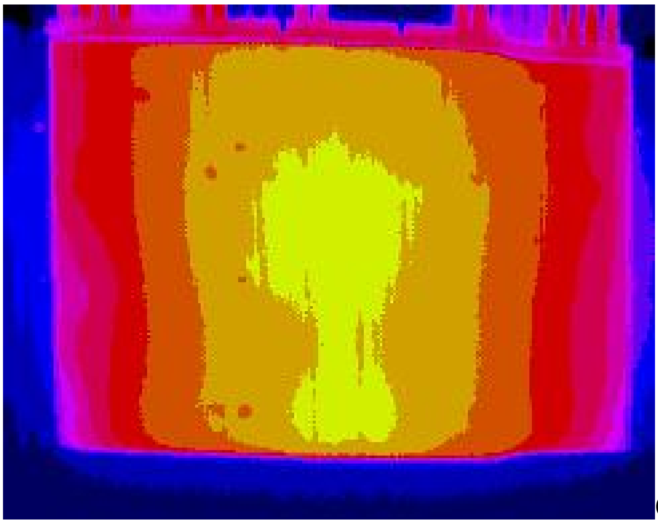


Figure 4. Aluminum encapsulated APG power supply chassis for an airborne electronics application. The conductance of this k-Core chassis was nearly four times higher and had an 11% lower mass than the baseline aluminum part of the same geometry.

In this particular application, the baseline aluminum chassis became thermally limited and a higher conductance material was required. Performance upgrades increased its dissipated power and due to weight and volume constraints, the chassis could not be made larger. The solution was to replace this baseline aluminum chassis with an aluminum encapsulated APG chassis. Figure 4 presents a photograph of the replacement k-Core chassis.
The performance of the aluminum encapsulated chassis is shown in comparison to the baseline aluminum design (Figure 5). The conductance of the chassis was tested and found to be nearly four times greater than the baseline aluminum components with an 11 percent lower mass. These measured results show a clear advantage in conductance and weight management, two crucial issues in the development of advanced thermal transport devices.



Conclusion

The significance of providing robust, reliable, high conductivity cooling solutions to the high performance electronics market is dramatic. As electronics have become more and more powerful, and more and more tightly packaged, power densities have increased enormously— resulting in the need to dissipate greater and greater amounts of heat in order to keep a circuit within its operating temperature range. Existing solutions are becoming less and less able to handle the current and future market requirements. In addition, other requirements of certain high performance electronics further complicate thermal management challenges. In applications in the military, commercial space and other high performance sectors, new, high conductivity, low mass, highly durable, passive (and therefore reliable) solutions are required.

k Technology, a Division of Thermacore, markets its encapsulated APG materials under the trade name k-Core. k Technology has developed the k-Core material into a viable product for thermal cores, heat spreaders and thermal straps (see www.k-Technology.com [1]). The k-Core material has been established and is being used on space systems, aircraft and land and sea systems. The high conductivity of this encapsulated APG materials system reduces operating temperature in electronics chips, which in turn precipitates smaller electronics packages with equivalent power or higher power packages in the same envelope.

Continued application of the encapsulated APG material in designing thermal management systems will present exciting new innovative solutions to passive thermal management. The APG encapsulation scheme combines the desired properties of two materials in a configuration that allows the cost-effective optimization of the assembly. Inquiries regarding the encapsulated APG material can be made by contacting the author.

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[1] http://www.k-Technology.com